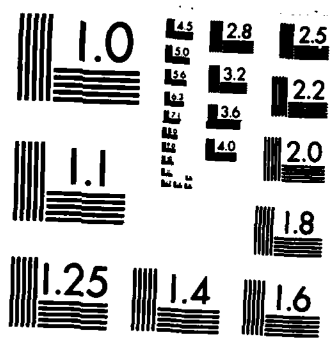
AD-A154 873 AN INTRODUCTION TO SATELLITE ORBITS(U) ROYAL AIRCRAFT ESTABLISHMENT FARNBOROUGH (ENGLAND) R H GOODING SEP 84 RAE-TM-SPACE-344 DRIC-BR-94394 1/1

UNCLASSIFIED F/G 22/3 NL

END

FILMED

DTIC




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

REPRINT





TECH. MEMO
SPACE 344

TECH. MEMO
SPACE 344

ROYAL AIRCRAFT ESTABLISHMENT

# AN INTRODUCTION TO SATELLITE ORBITS

by

R. H. Gooding

September 1984





Procurement Executive, Ministry of Defence
Farnborough, Hants

1

ROYAL AIRCRAFT ESTABLISHMENT

Technical Memorandum Space 344

Received for printing 12 September 1984

# AN INTRODUCTION TO SATELLITE ORBITS

by

R. H. Gooding

SUMMARY

An elementary introduction to artificial satellite orbits is presented, with a convenient classification in terms of the height of perigee and apogee, orbital inclination being another parameter of importance. The main sources of orbital perturbation are described, and special attention is paid to orbits with repeating ground-track. Additional keywords: mathematical curves.

## LIST OF CONTENTS

# 1 INTRODUCTION

## 1.1 Unperturbed orbits

The motion of an artificial satellite about the Earth is best introduced by reference to the concept of an unperturbed orbit. This is the mathematical curve in space that the satellite would follow if it were subject only to the Newtonian inverse-square-law force of attraction due to a uniform spherical Earth. Such an unperturbed motion is often described as Keplerian because its analysis was originally based on the three empirical laws that Kepler derived by examining the motion of the planets around the sun.

The mathematical curve just referred to is a conic section confined to a plane passing through the Earth's centre of mass. (Here, and even when we consider perturbed orbits, it is legitimate to ignore the Earth's own orbital motion, so that its centre of mass is a proper point for adoption as the origin of the various coordinate systems customarily employed.) Thus it can be an ellipse, of which a circle is merely a particular case, a parabola or a hyperbola. A satellite in parabolic or hyperbolic orbit possesses enough energy for effective escape from the Earth's gravitational field and we are not concerned with these orbits. Only the ellipse is a closed curve in which revolutions of unperturbed motion continue for ever.

## 1.2 Orbital elements

A Keplerian elliptic orbit may be specified mathematically by a set of six parameters or 'orbital elements' - six because this is the number of arbitrary constants required when integrating a second-order differential equation for vectors in three-dimensional space. For the purpose of orbit characterization, however, three parameters suffice, and broadly speaking these specify its size, shape, and orientation in space. The size of the orbit may be specified by the length of the ellipse's major axis and it also happens (by Kepler's third law) that this quantity is given directly by the 'orbital period' (the time to trace out one revolution): the shorter the major axis, the shorter the orbital period. Again, the shape is given by the eccentricity, which measures the deviation from circularity, being zero for an exact circle and approaching unity as the ellipse approaches the opposite extreme, a parabola. For our purpose, however, it is most convenient to specify size and shape together, by a different pair of parameters that have an immediate meaning for the Earth-bound observer.

## 1.3 Perigee and apogee

To introduce the pair of parameters just referred to, it must first be remarked that the ellipse is not symmetrically disposed about the Earth's centre of mass, since this point is at one focus of the ellipse, not its centre. (The inevitable question "What about the other focus?" can only be answered by saying that it is best forgotten - it necessarily varies from one ellipse to another and is wholly devoid of significance.) The effect of the asymmetry is that the geocentric distance of the satellite does not have its minimum value at

the ends of the orbit's minor axis, but instead has it at the end of the major axis that is closer to the significant focus; this point is known as perigee (for planetary orbits it is 'perihelion'). Similarly, the maximum geocentric distance is attained when the satellite is at the far end of the major axis, and this point is known as apogee. It only remains to reference the perigee and apogee to the Earth's surface rather than its centre, so that we have a 'height' rather than 'distance', and we have the pair of parameters required.

### 1.4 Orientation of the orbital plane

The third parameter required for orbit characterization relates the orientation of the orbital plane to the Earth's equatorial plane. The angle between the two planes is the (orbital) inclination. Its value varies from zero (for an orbit within the equatorial plane, with the satellite travelling in the same directional sense as the Earth's rotation), through 90° (for an orbit such that the satellite passes directly over the north and south poles), to 180° (for an orbit such that the satellite is again confined to the equator but now has a retrograde motion). A pair of orbits of supplementary inclination are in many ways similar, for example in that the satellites cover the same latitude range of variation for both, but orbits of inclination less than 90° are overwhelmingly more common than those of inclination greater than 90°. This is because of the economy factor in achieving direct orbit, as opposed to retrograde orbit, since a slingshot-type advantage can be taken of the 'direct' rotation of the launch site about the Earth's polar axis.

### 1.5 Summary for unperturbed orbits

We can summarize our most useful set of orbit-characterizing parameters as follows, therefore:-

* $h_p$ - the height of perigee (km)
* $h_a$ - the height of apogee (km)
* i - the orbital inclination (deg) .

Values can only be derived for $h_p$ and $h_a$ if a value is assumed for the radius of the Earth (to be subtracted from geocentric distance to give height). It is normal to use a fixed value of the equatorial radius (6378 km) for this purpose, even if (in an extreme case) perigee is actually over one pole and apogee over the other.

## 2 CLASSES OF ORBIT

### 2.1 Introductory remarks

It has become convenient, particularly in the military context, to identify up to half a dozen broad classes of orbit, since the statistical distribution of the orbital population is far from random. The division is not clear-cut, however, so that the classification is necessarily somewhat arbitrary. The classification suggested here

involves five classes of orbit, characterized entirely by the values of $h_p$ and $h_a$, but another system might be preferred in the future, in particular with some weight given to i.

## 2.2 Low Earth Orbits (the LEO class)

The LEO class is defined by an upper limit for $h_a$, a suggested (but completely arbitrary) value being 3000 km. (The need to avoid the Van Allen radiation belts is a factor here; the effects of the inner belt are most severe between heights of about 2000 km and 6000 km, depending on latitude, the corresponding figures for the outer belt being about 12000 km and 30000 km.) The value of $h_p$, which cannot exceed $h_a$ by definition, is otherwise unrestricted, though rarely less than 150 km. (Low perigee implies a short lifetime, and below 110 km it becomes impossible for most satellites to orbit at all.) This is obviously the easiest class of orbit to achieve, which is why the earliest satellites were in class LEO, but the normal reason for a satellite to be LEO is that this is just what is required, important applications being to surveillance, reconnaissance, meteorology, oceanography, etc, in fact to remote Earth sensing generally (though not all remote sensing is from LEO satellites). The LEO class covers the whole range of i, but two values are worth particular mention: $90^o$, because this permits total coverage of the Earth (though visibility of and from the poles is still of course possible, once per revolution, with orbits that are sufficiently close to polar - the elevation angle can then no longer reach $90^o$); and around $98^o$ (the precise value depends on orbital height), because this permits an extended lifetime free of solar eclipse (as explained in section 3.4)

## 2.3 Highly Elliptic Earth Orbits (the HEEO class)

The HEEO class is defined by a lower limit for $h_a$, a possible (but completely arbitrary) value being 20000 km, in conjunction with an upper limit for $h_p$, for which the (equally arbitrary) value of 3000 km is suggested. The commonest basis for such an orbit is that there is a need for an asymmetric configuration of apogee and perigee, one being at high latitude in the northern hemisphere and the other at high latitude in the southern hemisphere. With the USSR Molniya system of satellites, for example, the requirement is for a high northern apogee, at which point the satellite's velocity must be as low as possible, and for a correspondingly low (southern) perigee - the precise values of $h_p$ and $h_a$ are constrained by the need for an orbital period of 12 h, so that alternate apogees are at the same longitude above the USSR (see also later sections, in which the need for a particular inclination, viz $63.4^o$, will be explained). An example of an entirely different HEEO requirement arises with the transfer-orbit phase of a geosynchronous mission; this type of orbit is more symmetric than the Molniya orbit, in that perigee and apogee are on or near to the equator and not at the extreme latitudes.

.4 High Sub-synchronous Earth Orbits (the HSEO class)

The HSEO class is defined by an upper limit of about 35500 km for $h_p$, and by exclusion from the other classes. It follows that the orbital period must be less than 24 h, which is why the orbits are escribed as sub-synchronous. It is clear that a vast range of orbital ize and shape is covered, but there have been relatively few specimens rom the class so far. Perhaps the best example is provided by the rbits of the US Navstar/GPS satellites; these are nominally circular, t height about 20000 km (more precisely such as to make the orbital eriod 12 h) and at an inclination that has been reduced from 63° to 5° now that the development stage of the programme is complete.

.5 Geosynchronous Earth Orbits (the GEO class)

This is the classical orbit, proposed by Arthur C Clarke in 1945, hat has an orbital period of just under 24 h to match the Earth's otation rate (it is the sidereal day of 23h 56m, rather than the solar ay of 24h, that has to be matched). The corresponding height is 5790 km, for a circular orbit, but to allow for a tolerance on the rbital period, together with a considerable degree of eccentricity, we an specify that $(h_p + h_a)/2$ must lie between 35500 km and 36000 km and hat $h_p$ must exceed 3000 km (to exclude HSEO orbits). The prime unction of the GEO class is to provide an unbroken coverage capability or a communications satellite (e.g MOD's Skynet satellites). There is ometimes confusion between a geosynchronous orbit and a geostationary rbit: the latter is merely a particular case of the former in which by virtue of zero values for both the eccentricity and the nclination) the satellite remains at all times above the same point of he Earth's surface. (The ground-track for the general geosynchronous atellite takes the form of a distorted figure-of-eight that, for n unperturbed orbit, is closed.)

.6 Super-synchronous Earth Orbits (the SEO class)

The SEO class includes all orbits not covered by the other lasses. This implies that $(h_p + h_a)/2$ must exceed 36000 km and that $h_p$ must exceed 3000 km.

PERTURBATIONS

.1 Introductory remarks

We have thus far supposed our satellite to move in a Keplerian llipse, resulting from the influence of nothing but n inverse-square-law force of attraction. This is realistic insofar s the residual force in practice accounts for only some 0.1% of the otal force, and it is therefore natural to think of the satellite as oving in a path that can be described by the normal elements of n ellipse, but that the ellipse they specify is no longer fixed and he elements no longer constant; in particular, the path is no longer losed and the concept of orbital period, though still useful, is no onger precise. The (relative) smallness of the perturbing forces eans that their effects can often be neglected over short periods of

time (up to a day or two perhaps), but over long periods they are of the utmost importance.

## 3.2 Sources of perturbation

The four main natural sources of perturbation are the following:-

* atmospheric drag
* asphericity of the Earth
* lunisolar attraction
* solar radiation pressure

and we consider the effects of each of these in turn. Other sources (Earth tides for example) must sometimes be considered, and artificially induced perturbations must also be taken into account of course - a few words on these will be in order before returning to natural perturbations.

A possible classification of artificial changes of orbit is into 'deliberate effects' and 'incidental effects'. A deliberate effect may be so violent (as when an apogee motor is fired) that the resulting orbit is best regarded as an entirely new one, rather than a perturbation; at the other extreme, its purpose (as with station keeping, to be discussed in section 4.2) may be to preserve the status quo by cancelling the effects of a natural source of perturbation. An incidental effect (usually small enough to be neglected entirely) may be inevitable, as when the gas-jet thrusters used in attitude control are not completely balanced; on the other hand it may be quite unforeseen, when a leak is present for example.

We now consider the four main sources of natural perturbation.

## 3.3 Atmospheric drag

The range of variation of drag effects is enormous. Drag can be totally neglected for SEO, GEO, most HSEO, and even many HEEO satellites. For most LEO satellites, on the other hand, it can not be neglected and is often the dominant force (in particular for low-density balloon satellites). If a satellite is affected at all by drag, then it will ultimately be destroyed by drag, its fate being to burn up like a meteorite. For an orbit with $h_a$ significantly in excess of $h_p$, the drag may be regarded as effective only at perigee - the effect of the air resistance is a loss of energy, which lowers the height of the next apogee. Thus $h_a$ decreases much more rapidly than $h_p$ and the orbit becomes progressively more cicular, whilst the orbital period also decreases. An apparent paradox arises here, that is not always properly understood, since the mean velocity of the satellite increases as the orbital period decreases, so that the effect of resistance is to produce an acceleration rather than a retardation! There is no real contradiction, however, since the velocity at a fixed

igee has to decrease for the mean velocity around the orbit to rease.

Asphericity of the Earth

The oblateness (flattening) of the Earth leads to perturbing ces that for LEO satellites are of about the same order of magnitude the drag force. The forces reduce with height much more gradually in does the drag force, however. For HEEO (sub-synchronous), HSEO l GEO satellites, and even for the lower SEO satellites, the ateness force is the dominant perturbing force. It has negligible ect on the three orbital elements that have been explicitly defined, : there is a two-fold effect on the remaining elements that is isiderable and can be described without explicitly introducing these ments: first, the orbital plane precesses (rotates in a westerly ection for direct orbits, easterly for retrograde) about the Earth's ar axis (which is why i is unaffected); secondly, the orbit rotates thin its plane, so that apogee and perigee slowly move from one isphere to the other.

A little more must be said about these two effects. First, the metric nature of the precession dictates that it vanishes altogether : polar orbits ($i = 90^{o}$). Secondly, it is possible, with a suitable rograde orbit, for the easterly precession to be synchronized to the parent orbital motion of the Sun (at $0.9856^{o}$/day) about the Earth; s occurs for an orbit with a particular value of i (upwards of $96^{o}$, ng dependent on orbital height) and permits an orbit that has been : up to be eclipse-free to continue to be eclipse-free, as remarked section 2.2. Thirdly, the other effect is not symmetric in the way it the precession effect is, but there is nevertheless a value of i : which it disappears, viz $63.4^{o}$; this is the value, referred to in tion 2.3, at which perigee and apogee remain in their respective ispheres.

The oblateness effect arises from a perturbing force that is mmetric with respect to the Earth's equatorial plane and, more portant, is independent of the satellite's longitude. This force counts for about 99.9% of the total force associated with the phericity, but the remaining 0.1% can have an importance out of all oportion to its magnitude. This occurs, in particular, when the tellite's orbital period is commensurate with the period of the th's rotation - the resulting phenomenon is known as resonance and s importance is explained in section 4.2.

5 Lunisolar attraction

The essential difference between lunisolar forces and the forces e to drag and asphericity is that the lunisolar forces increase with bital height whilst the others decrease with height. Thus lunisolar fects can normally be ignored altogether for low orbits, but for per-synchronous orbits they are likely to dominate. In the short m the effects are associated with the actual positions of the two avenly bodies, but in the long term what is important is the

rientation of their orbits relative to the Earth's equatorial plane. n fact the lunar and solar orbits each induce a precession of the atellite's orbital plane that is similar to that due to oblateness but onsists of a rotation about the axis normal to the orbital plane of he appropriate heavenly body rather than normal to the equatorial lane. It follows that both bodies have a tendency to alter i. It is or this reason that many GEO satellites (all the Skynets in articular) are launched with an initial i of (typically) about 3.5°; he initial orientation of the orbital plane is chosen such that i mmediately starts to decrease and does not again rise to its initial alue until after about 7 years. (If initialized at zero, i would ncrease at a gradually decreasing rate of about 1°/yr over this length f time.)

.6 Solar radiation pressure

The force due to solar radiation pressure resembles the force due o atmospheric drag, in being highly dependent on the satellite's eometry (size and shape) as well as its mass. Unlike the forces so ar considered, however, it is essentially independent of the orbit the atellite is in. (The reason that the perturbations due to solar ravity increase with orbital height is that these perturbations, nlike those due to solar radiation, are differential in nature, ecause the effects on the Earth itself have to be subtracted from the irect effects on the satellite.) Thus this source of perturbation is ormally overshadowed by at least one of the others and for many urposes the effects can be neglected altogether.

There are two reasons why, for example with the Skynet atellites, important special problems may arise with the computer odelling of the solar radiation effects. The first is a corollary of he relevance of the satellite's geometry and also of the role played y the reflective properties of the external surface of the satellite. hese factors can complicate the modelling enormously, and it is often ecessary to introduce the empirical determination of one or more pecial parameters. (This is almost always necessary in the epresentation of drag effects for satellites in the LEO class.) The ther special problem is associated with eclipse. As the satellite nters the Earth's shadow, the solar radiation pressure rapidly ttenuates. This is a situation that arises with none of the other orces, and a complication in the modelling is therefore inevitable.

ORBITS WITH REPEATING GROUND-TRACK

.1 The application

The relationship of the period of the Earth's diurnal rotation to he satellite's orbital period leads to orbits of a particular type of pplication. This occurs when the ratio of the two periods is either ntegral or can be expressed as a fraction with a small denominator. f the ratio is m/n, say, the significance of this is that the atellite makes m revolutions in n days (sidereal, with allowance for recession of the orbit's nodes), after which the satellite is above xactly the same point of the Earth as at the beginning of the n-day

l.

The most obvious application is to communications satellites, satellites in the GEO class are precisely the satellites that are .lly commensurable with 1/1 ratio. Again, the Molniya satellites : HEEO class have 12h period, for which the ratio is 2/1, and this ;o true of the Navstar satellites of the HSEO class.

The essence of the exact m/n commensurability is that the .ite's ground-track repeats (precisely, apart from the question of 'bations, to be considered in a moment) after n days, and :age can be taken of this for renewed surveillance of a particular l feature, for example. A more subtle requirement is to off-set ıtellite's orbital period slightly from the value required to give :ise repetition after n days, so that the ground-track slips in :rolled manner and the entire Earth (below the latitudes ıined by the inclination) is eventually covered uniformly. This ıe mission design for Seasat 1, an oceanographic satellite in :imately 43/3 orbit, the precise values of m and n being chosen so ›ver a period of 5 months the equator crossings would form a grid ı mesh interval of about 18.5 km.

Resonant perturbations

The objective of an orbit with a repeating ground-track is to 're a high degree of regularity in regard to the satellite-Earth :ry. For an almost geostationary satellite there is the very ıl case that the satellite hardly moves in the sky.

As soon as perturbations are considered, however, this very ırity induces an especially disturbing effect on the orbit, ;e certain effects that would normally vary sinusoidally, ;ing to zero over many orbital revolutions, take on a 'resonant' :ter so that unidirectional contributions to the variations in the ıl elements are generated. The effects are most noticeable in the Lite's inclination and orbital period, because these normally : so very slowly. The variation in i is not important for most ;es, being small (because the longitude-dependent forces Lated with the Earth's asphericity are themselves so small, as has ıoted), but the variation in period can be of the utmost :ance, since over many revolutions it can produce an enormous : on the position of the satellite within its orbit.

This last feature of satellite perturbations is of special :ance for geosynchronous orbits, where it operates even for orbits :ero i (which with circular orbits is only true for 1/1 ınce). The situation may be summarized by noting that there are :able longitudes, at about 75° East and 105° West; at (but only ıese two longitudes can a satellite remain indefinitely :ation'. If a satellite of GEO class starts its life at any other :ude, it will inexorably begin to drift towards the nearer stable :ude, an essentially simple harmonic motion being set up about Longitude; the period of the motion is usually of many months. to stop this motion (indeed, to reverse it temporarily) that

.tal manoeuvres are required for communications satellites; such )euvres constitute 'east-west station keeping', which can be the ı drain on a satellite's fuel during its operational lifetime. (The ' heavier drain occurs when 'north-south station keeping' is ıired to correct for lunisolar perturbations and maintain i close to ); north-south station keeping can be dispensed with, however, as seen in section 3.5, and it is not employed with the Skynets.)

# REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNCLASSIFIED

As far as possible this page should contain only unclassified information. If it is necessary to enter classified information, the box above must be marked to indicate the classification, e.g. Restricted, Confidential or Secret.

| 1. DRIC Reference (to be added by DRIC) | 2. Originator's Reference | 3. Agency Reference | 4. Report Security Classification/Marking |
|---|---|---|---|
| | RAE TM Space 344 | N/A | UNCLASSIFIED |

| 5. DRIC Code for Originator | 6. Originator (Corporate Author) Name and Location |
|---|---|
| 7673000W | Royal Aircraft Establishment, Farnborough, Hants, UK |
| **5a. Sponsoring Agency's Code** | **6a. Sponsoring Agency (Contract Authority) Name and Location** |
| N/A | N/A |

7. Title An introduction to satellite orbits

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference

| 8. Author 1. Surname, Initials | 9a. Author 2 | 9b. Authors 3, 4 .... | 10. Date | Pages | Refs. |
|---|---|---|---|---|---|
| Gooding, R.H. | | | September 1984 | 11 | - |

| 11. Contract Number | 12. Period | 13. Project | 14. Other Reference Nos. |
|---|---|---|---|
| N/A | N/A | | |

15. Distribution statement
(a) Controlled by –
(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Orbits*. Artificial satellites*.

17. Abstract

An elementary introduction to satellite orbits is presented, with a convenient classification in terms of the height of perigee and apogee, orbital inclination being another parameter of importance. The main sources of orbital perturbation are described, and special attention is paid to orbits with repeating ground-track.

1/0169

# END

# FILMED

7-85

# DTIC